Experimental Results from SHIVA Star Vacuum Inductive Store/Plasma Flow Switch Driven Implosions

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Abstract

Using a 1313 μF, 3 nanohenry, 120 kV, 9.4 MJ SHIVA Star capacitor bank, we have performed vacuum inductive store/plasma flow switch (PFS) driven implosions of low mass (200-400 μg/cm^2) cylindrical foil liners of 2 cm height and 5 cm radius. This technique employs a coaxial discharge through a plasma armature, which stores magnetic energy over 3 to 4 μs and rapidly switches it to an imploding load upon exiting the plasma armature from the coaxial gun muzzle. The current transferred to the load by the PFS has a rise time of less than 0.2 μs. With 5 MJ stored energy, we have driven fast liner implosions with a current of over 9 Megamperes, obtaining an isotropic equivalent 2.7 Terawatt, 0.5 Megajoule X-ray yield.

Introduction

Since the early 1970's, the Air Force Weapons Laboratory has been investigating the electromagnetic implosion of cylindrical plasma liners to produce high energy density plasmas and intense radiation pulses[1]. In 1976-1978, we achieved direct capacitor drive, 1.0 to 1.5 μs implosions of aluminum and aluminized plastic liners with capacitive energy stores of 0.7 to 1.3 Megajoules, discharge currents of 7 to 12 Megamperes, resulting in 0.5 to 1.0 Terawatt radiation pulses, 50 to 200 kilojoule isotropic equivalent yield[2]. Anisotropy effects are expected to increase the magnitude of the radiation yield, since the optically thick pinch plasma is elongated along the observing direction. In order to scale these results to multi-megajoule energies, we have investigated inductive store pulse compression techniques, including air core inductive store/fast fuse opening switch/surface flashover closure switches[3] and vacuum inductive store/plasma flow switching[4]. Plasma flow switching has the important advantage of lower voltage across vacuum/solid dielectric interface, a mechanically simpler design and less expensive manufacture.

EXPERIMENTAL GEOMETRY

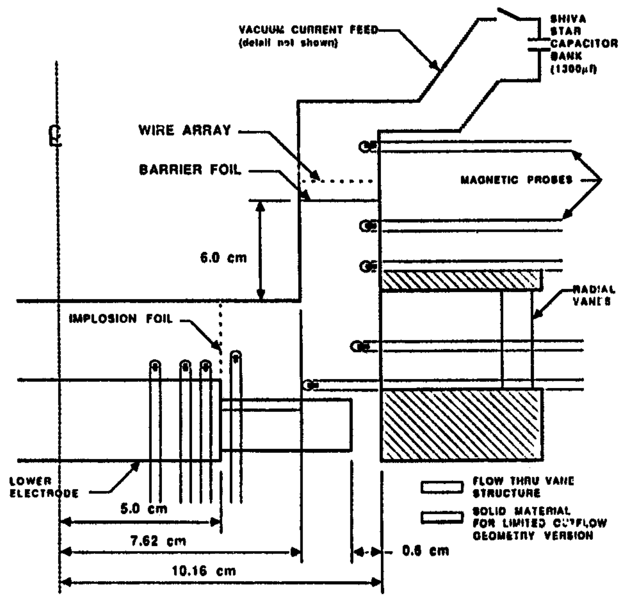

Figure 1. Plasma flow switch geometry.

The plasma flow switch (PFS) technique, originally studied by Turchi et al.[5], employs a vacuum discharge through a plasma armature which stores magnetic energy for several microseconds and rapidly transfers current and energy to a load when the plasma armature exits the vacuum inductive store structure. We have investigated coaxial, cylindrical/radial and staged vacuum inductive store geometries. In this paper, we discuss results from a cylindrical liner implosion load driven by a coaxial vacuum inductive store.

Experiment Configuration

During the experiments described here, the SHIVA Star capacitor bank with 5.0 MJ stored energy is discharged through a vacuum coaxial gun, accelerating a plasma armature by J × B forces, storing magnetic energy over 3 to 4 μs and then rapidly transferring current and energy to a cylindrical foil liner implosion load. The geometry is illustrated in Figure 1. The current transfer time is about 0.2 μs, which is on the order of the cylindrical implosion gap axial dimension divided by the velocity of the plasma armature as it exits the coaxial gun muzzle.

The plasma armature is created by the electrical explosion of an array of wires and its impact on a plastic barrier foil. The armature is designed so the average areal mass density (mass per unit area) of the assembly is proportional to $1/r^2$. The armature is formed from an array of 1.8 to 2.0 mil (4.57×10^{-5} to 5.08×10^{-5} m) diameter aluminum wires and a stretched

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14. ABSTRACT
Using a 1313 ~F, 3 nanohenry, 120 kV, 9.4 MJ SHIVA Star capacitor bank, we have performed vacuum inductive store/plasma flow switch {PFS) driven implosions of low mass {200-400 ~g/cm2) cylindrical foil liners of 2 em height and 5 em radius. Â·This technique employs a coaxial discharge through a plasma armature, which stores magnetic energy over 3 to 4 ~s and rapidly switches it to an imploding load upon exiting the plasma armature from the coaxial gun muzzle. The current transferred to the load by the PFS has a rise time of less than 0.2 ~s. With 5 MJ stored energy, we have driven fast liner implosions with a current of over 9 Megamperes, obtaining an isotropic equivalent 2.7 Terawatt, 0.5 Megajoule X-ray yield.

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400±20 μg/cm^2 Mylar foil a distance of 0.635 cm downstream from the wire array. The mass of the assembled plasma armature is approximately 100 mg. The coaxial gun has a 7.62 cm inner radius, 10.16 cm outer radius. The distance from the gun muzzle to the Mylar foil is 6.0 cm. The discharge inductance up to the position of the Mylar foil is 19 nanohenries; this includes the 3 nanohenry capacitor bank/parallel plate transmission line inductance, about 3 nanohenries for a series 0.94 meter long, 2.125 cm^2 cross section aluminum foil safety fuse and the vacuum/solid dielectric interface and about 13 nanohenries for the vacuum current feed. The vacuum current feed is baffled to attenuate UV photons from the discharge and to protect the insulator from ablation and breakdown. The safety fuse absorbs energy late in the discharge and protects the SHIVA Star bank in the event of a vacuum/solid dielectric interface failure.

The implosion load is a 5 cm radius, 2 cm tall, 200 to 400 μg/cm^2 aluminized Formvar seamless cylindrical foil. In the experiments to date, this foil has a concave bow of about 1 mm amplitude (due to the Formvar surface tension) which is an important limitation on the implosion performance.

The vacuum power feed electrodes are aluminum and are anodized from the dielectric/vacuum interface to the wire array. The gun electrodes are gold plated aluminum. Anodization reduces field emission and the gold plating reduces ablative gap closure.

The electrodes within the initial radius of the cylindrical foil have 2 cm diameter holes at their center for axial radiation diagnostic access. We have performed experiments with closed and with partially open outer conductors below the coaxial gun muzzle (at the same axial position as the cylindrical implosion electrode gap). The partially open radial vane design is used only when radial diagnostic access is desired. The implosion electrodes are formed by the muzzle end of the coaxial gun electrode and an electrode 2 cm beyond the muzzle which is not initially electrically connected to the coaxial gun outer electrode. After plasma armature switching, this more distant (lower) implosion electrode is electrically connected to the coaxial gun outer electrode.

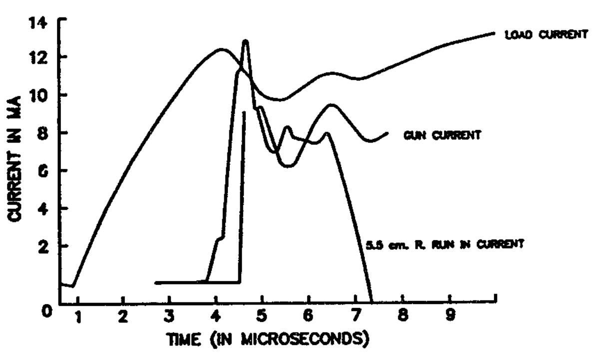

Figure 2. Experimental current delivery.

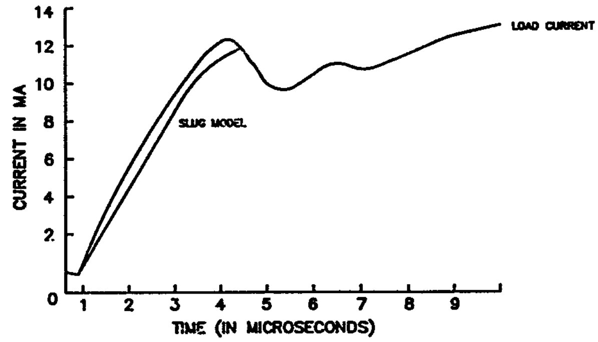

Figure 3. Observed and predicted total current.

In the initial experimental design, the lower implosion electrode consisted of radial vanes from the 5 cm initial foil radius to a 9.52 cm outer radius with a 0.64 cm gap between this electrode outer radius and the axial extension of the 10.16 cm radius outer electrode of the coaxial gun. This design was to allow unrestricted plasma flow from the switching region while trapping the discharge magnetic field. With this design, the experimental transfer efficiency of current to a 200 μg/cm^2, 5 cm radius implosion load was 40 to 50%, with the remainder of the current diffusely distributed in the switching region. For very massive loads at the 5 cm radius, the current delivery improved substantially. (The initial results from this experimental series were reported by Baker et al.[4] at the 1985 IEEE Pulse Power Conference.) These results were in substantial agreement with the subsequent 2-D MHD code predictions obtained by Buff et al. using the MACH2 computer code[6-8]. Numerical simulations with MACH2 predicted that using a more restrictive outflow boundary condition would greatly increase current delivery to lower mass implosion loads. We accomplished this by making the lower electrode solid out to a 7.62 cm radius while retaining the radial vane structure at larger radii. 2-D MHD calculations of plasma flow switch driven plasma liner implosions for our approximate experimental parameters were also reported by Lindemuth[9]. In those calculations, he emphasized implosion performance as a function of initial radius. His results agreed qualitatively with the results of Buff et al.[8]

Results

With this change to a more restrictive outflow geometry, we obtained the current delivery illustrated in Figure 2. The ratio of current delivered to the initial load radius is 80 to 100% of the total current for a 200 μg/cm^2 implosion foil. This is a factor of two improvement over previously reported results. These results were achieved with the solid coaxial outer electrode and a solid axial extension. We have yet to perform a series of experiments with the restrictive outflow geometry and a partially open outer conductor.

The experimental diagnostics included Rogowski current probes, capacitive voltage probes, small single turn magnetic probes (with approximate cross-sectional areas of 10^{-6} m^2) and an array of X-ray vacuum photodiodes. The current and magnetic probes were calibrated after installation in the discharge chamber, but prior to installation in the transmission line of the SHIVA Star capacitor bank. The B-dot probes were calibrated in situ by discharging a small capacitor through the load in the discharge chamber prior to the installation of the wire and foil arrays. The accuracy of the probe calculation is estimated to be ±10%. The Rogowski coils monitored the load current, while the magnetic probes monitored the current at a number of locations in the discharge geometry (Figure 1). The experimental curves of Figure 2 show the total current, the muzzle (gun) current and the current adjacent to and outside the initial foil radius (where the probe is at 5.5 cm radius). The peak current was 12.2±1.2 Megamperes with a rise time of 3.3 μs. The current delivered to the initial foil radius exceeds 9.4 Megamperes, assuming the current is azimuthally symmetric, at a time approximately 3.75 μs after the start of the current flow. The current rise time at the initial foil radius is less than 0.2 μs.

A slug model incorporating the electrical circuit was used to predict the motion of the coaxial armature motion. The simulation indicated the armature would exit the muzzle at 3.4 μs with a current of 11.8 Megamperes. The input parameters of the model were 90 kV charge, 5.3 Megajoules stored energy, 19 nanohenries initial inductance and an armature mass of 99.6 mg. The 0-D slug code realistically models the time varying resistance of the safety fuse. A series resistance of 1 mΩ in addition to the safety fuse is used. The predicted and the observed current are shown in Figure 3. The small disagreement in the time behavior may be due, in part, to the loss of the armature mass (due to armature tilting).

Bank current, voltage and a typical X-ray vacuum photodiode trace are shown in Figure 4. The voltage peaks at about 4.1 μs into the current rise and the X-ray diode signal peaks about 4.25 μs. In the X-ray trace, the fiducial occurred at 4.2 μs. Notice the voltage signal starts to rise when the current passes its maximum at about 3.3 μs. We interpret this to mean the plasma armature is starting to exit the coaxial gun muzzle.

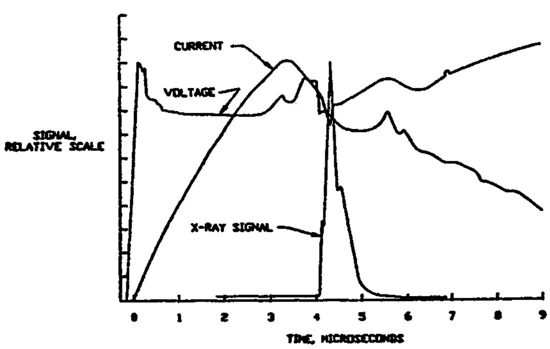

Figure 4. Normalized current, voltage and X-ray signals.

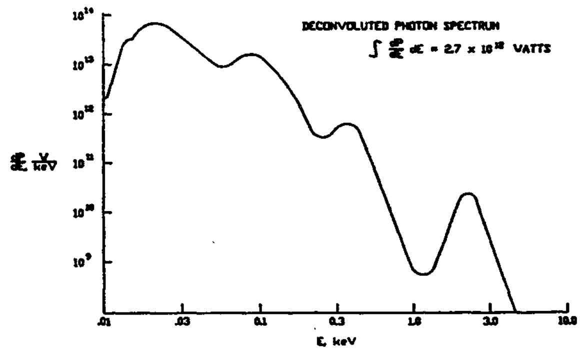

Figure 5. Deconvoluted radiation spectrum at peak emission power.

The X-ray signal has a double peak with the second peak about half the amplitude of the first for the 50 μg/cm^2 Formvar plastic filtered X-ray vacuum detector. (Formvar has an approximate stoichiometry of $C_5H_8O_2$.) The FWHM of this X-ray pulse is about 0.2 μs. The X-ray photocathodes were all aluminum. The X-ray photodiode detectors were filtered by materials with filter response functions covering the photon energy range from 15 eV to 3 keV. The deconvoluted radiation spectrum consistent with the array of signals is shown in Figure 5. This spectrum indicates a peak isotropic equivalent emission power of 2.7 Terawatts. The energy in the first pulse is over 0.5 Megajoules. The stored electrical energy is converted to radiation energy with approximately 10% efficiency.

We are now preparing to improve PFS driven plasma liner implosion performance by reducing foil bowing, using gas injection snowplow stabilization[10] and optimizing foil mass and geometry guided by 2-D MHD numerical simulations.

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